

Design and validation of production-suited vibroacoustic metamaterials for application in a vehicle door

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Abstract

In the presented work, vibroacoustic metamaterials are designed and validated for application in a vibroacoustic optimized vehicle door, focusing on a design suitable for production. This requires an efficient vibration reduction in the frequency range around 500 Hz with an aim to overcome limitations of existing solutions. Thus, metamaterial designs suitable for a mass production and exhibiting strong stopband behavior are needed. In this work, different concepts for the implementation of local resonant structures to compose vibroacoustic metamaterials are developed with respect to an economical and production-suited manufacturing. The proposed concepts and manufacturing techniques are initially tested on metallic plate demonstrators in different configurations. For an experimental validation, specific transfer functions are measured using a laser vibrometer. For the proposed concepts, stopbands are found in the intended frequency region. The gained knowledge will be used to develop a vibration-optimized vehicle door.

Introduction

Current trends in the automotive sector, such as electrification and autonomous driving lead to new challenges in noise, vibration, and harshness (NVH) requirements. Furthermore, comfort oriented NVH features become more important [1]. In terms of light weight and compact design, conventional measures are reaching their limits. This leads to a demand for lightweight, effective, and broadband frequency vibration reduction.

In the past years, vibroacoustic metamaterials (VAMM) have come to the fore as a promising solution to overcome the before-mentioned challenges [2,3,4]. This work will focus on VAMM based on local resonance effect for elimination of elastic waves in plate-like structures shown in Fig. 1. The so-called stop band behavior is induced by attaching local resonance structures on a subwavelength scale.

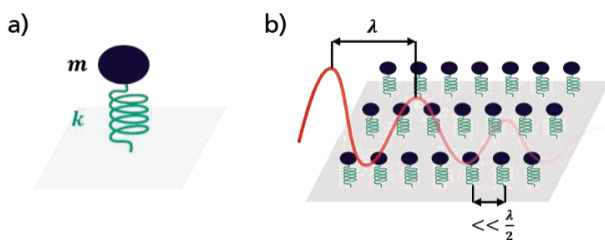


Figure 1: Concept of VAMM based on local resonance effect for elimination of elastic bending waves in plate-like structures - a) unit cell and b) cell compound

VAMM show a great potential in industrial application due to the flexible and compact design of resonance structures, the tunable frequency range and high lightweight potential. However, the development of VAMM solutions requires a sophisticated design. Furthermore, specific production processes are needed to manufacture small-scale, periodic structures with defined dynamic properties. The aim of the presented research is to overcome these challenges in design and production of VAMM and to enable a wide field industrial application. Therefore, a holistic design process as well as new manufacturing technologies and VAMM concepts are developed for large-scale production. The proposed design process, concepts and manufacturing technologies are demonstrated on vehicle door application shown in Fig. 2. In this paper, the concepts and manufacturing techniques are initially tested on metallic plate demonstrators.

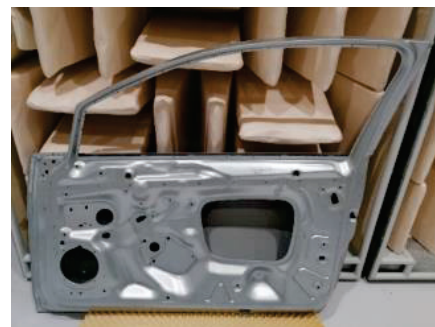


Figure 2: Demonstrator application of a vehicle door metal door frame

Production-suited Concepts

To enable industrial application of VAMM, economical concepts for local resonance structures and their integration in the target system are required. In the following, two concepts suitable for large-scale production are proposed.

Metal Concept

The metal concept shown in Fig. 3 represents a resonant structure which is made of a cut-out and bended-up metal strip with a mass added on top. The strip mainly drives the compliance of the resonator. The tip mass helps to tune the resonator to a specific resonance frequency and provides effective mass to the resonant mode. The resonators are designed to be arranged in a close compound to enable the placement of many resonators on a limited design space. The

compound is design for the manufacturing with punching and bending machines. For the validation of the production process, a demonstrate plate is considered. This demonstrator plate with a size of 300x200 mm² consists of a compound of 110 resonators attached to a steel base plate of 0.7 mm thickness.

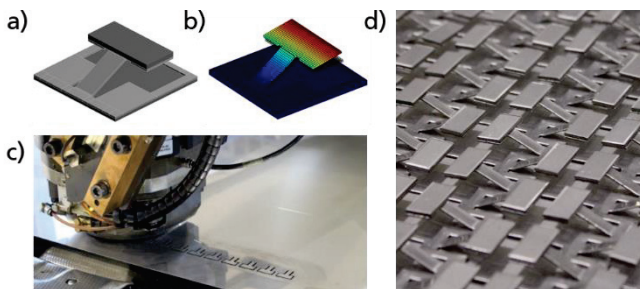


Figure 3: Production-suited metal concept - a) resonator on unit cell, b) unit cell local eigenmode, c) punching process to cut out metal strip and d) cell compound on demonstrator plate

Plastic Concept

The plastic concept shown in Fig. 4 represents a beam-like resonator. The horizontal beam mainly drives the compliance of the resonator, whereas the tip mass can be used to tune the resonance frequency. To create a resonator compound, seven resonators are connected. The concept is designed to be produced using an injection molding process. However, in the context of concept validation the first prototype is produced using additive manufacturing. The demonstrator plate with a size of 300x200 mm² consists of ten compounds of each seven resonators glued on to a steel base plate of 0.7 mm thickness.

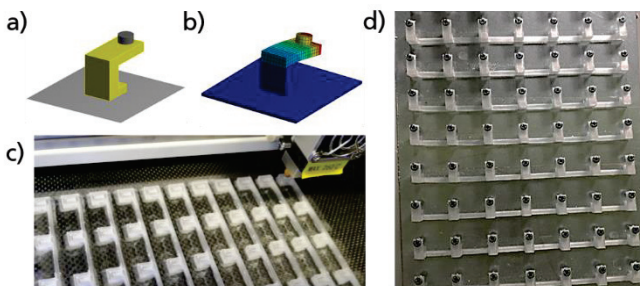


Figure 4: Production-suited plastic concept - a) resonator on unit cell, b) unit cell local eigenmode, c) additive manufacturing for prototyping d) cell compound on demonstrator plate

Numerical Design

To evaluate the stop band behavior of the proposed concepts, numerical simulation on unit cell level, as well as on demonstrator level are performed. By the calculation of dispersion curves the character of wave propagation in a periodic structure can be estimated by means of a single unit cell [5,6]. The propagation characteristics are given by the complex wave vector $\mu = \mu_R + i\mu_I$ over the wave frequency f . The real part μ_R indicates an amplitude reduction and the imaginary part μ_I a phase change of the propagating wave per unit cell. In the presence of damping, stop bands can be found as frequency regions with a high amplitude reduction μ_R . To analyze the stop band behavior on the finite demonstrator

plates harmonic analyses are performed. By comparing averaged frequency response function of the finite demonstrator plate and the base plate, the stop band behavior can be seen.

Metal Concept

The resonator shows its first resonance frequency at 330 Hz. The effective mass of the corresponding eigenmode amounts 1.5 g. A low structural damping ratio of 0.5 % is assumed. The damped 1D dispersion curve for waves travelling through the unit cell can be seen in Fig. 5. By looking at the real part μ_R one can see the existence of a stop band between approx. 320 and 380 Hz. Due to the low amount of damping the stop band leads to a high amplitude reduction.

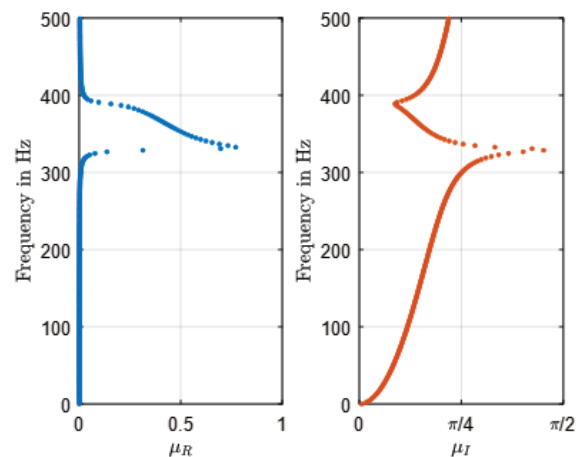


Figure 5: Complex wave vector of unit cell of metal concept - μ_R indicating amplitude reduction and μ_I indicating phase change per unit cell in stop band region from approx. 320 to 380 Hz

This behavior can also be seen on the finite demonstrator plate. A harmonic analysis is performed for the bare plate and the plate with the attached resonator compound. On the averaged acceleration frequency response function in Fig. 6 the deep stop band can be seen.

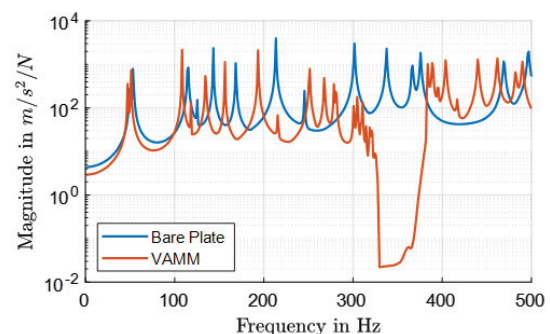


Figure 6: Magnitude of averaged acceleration frequency response function showing a stop band behavior on metal concept demonstrator plate from approx. 320 to 380 Hz

Plastic Concept

For the plastic concept the resonance frequency is much higher at 520 Hz due to the smaller effective mass of just

0.8 g. The damping is assumed to be higher with a structural damping ratio of 7 %. The damped 1D dispersion curve for waves travelling through the unit cell can be seen in Fig. 7. Due to the higher damping, the real part μ_R indicating an amplitude reduction is lower. However, the stop band is wider. Additionally, one can see that for high frequencies a significant amount of amplitude reduction is present.

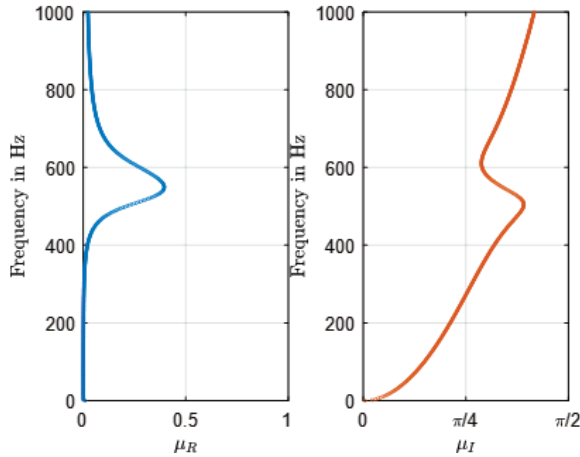


Figure 7: Complex wave vector of unit cell of metal concept - μ_R indicating amplitude reduction and μ_I indicating phase change per unit cell in stop band region from approx. 520 to 620 Hz

This behavior can also be seen on the finite plate demonstrator. The averaged acceleration frequency response functions of the bare plate and the VAMM are compared in Fig. 8. The stop band is less deep but much wider than with the metal concept. Furthermore, the damped system behavior can also be seen in the higher frequency region up to 1000 Hz.

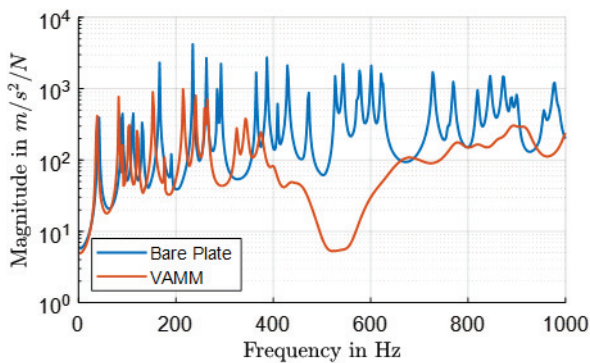


Figure 8: Magnitude of averaged acceleration frequency response function showing a stop band behavior on metal concept demonstrator plate from approx. 400 to 650 Hz

The numerical simulation shows that a stop band behavior is assumed to be present in the periodic system, as well as in the finite demonstrator plates.

Experimental Validation

To validate the stop band behavior of the proposed concepts experimental investigations are made. Firstly, the resonator properties are evaluated by placing them on a shaker. By measuring the force and acceleration, the dynamic mass of the

resonators can be analyzed. Secondly, the demonstrator plates are investigated by measuring averaged acceleration frequency response functions. Therefore, the plates are suspended on elastic bands to ensure free velocity boundary conditions. The plates are excited by a shaker on the lower edge and the surface normal velocities are measured on the upper edge using a laser scanning vibrometer.

Metal Concept:

The dynamic mass of the metal resonator is shown in Fig. 9. The resonance frequency indicated by the peak at 250 Hz is much lower than predicted. One reason could be the contact between the bend-up metal strip and the baseplate. However, due to the high and clear peak one can see the undamped behavior of the system.

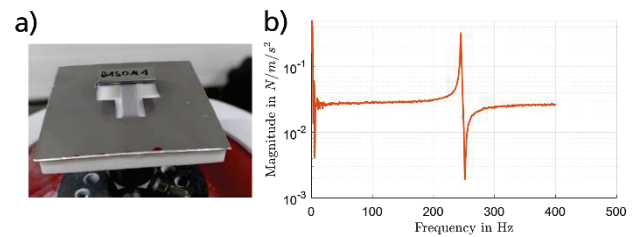


Figure 9: Experimental validation of single metal resonator - a) resonator on shaker and b) resonance peak at approx. 250 Hz in magnitude of dynamic mass

The measurement and comparison of the averaged acceleration frequency response functions for the bare plate and the VAMM are shown in Fig. 10. A stop band behavior can be seen between 240 and 300 Hz. However, the stop band is not as deep as in the numerical prediction. A reason for this could be a variation of the resonance frequencies due to production tolerances. This effect has to be further investigated.

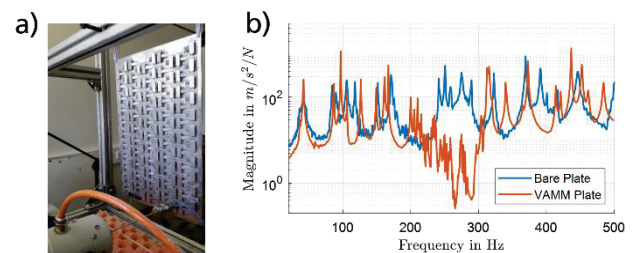


Figure 10: Experimental validation of metal concept demonstrator plate - a) excitation of plate in free velocity boundary conditions and b) stop band behavior in magnitude of averaged acceleration frequency response function

Plastic Concept:

The dynamic mass of the plastic resonator is shown in Fig. 11. The resonance frequency is indicated by the peak at 520 Hz. Due to a higher amount of damping, the peak is much smaller than the one from the metal concept.

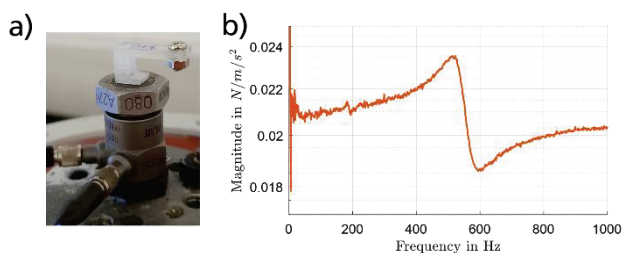


Figure 11: Experimental validation of single plastic resonator - a) resonator on shaker and b) resonance peak at approx. 520 Hz in magnitude of dynamic mass

This behavior can be validated by looking on the frequency response functions of the finite demonstrator plate shown in Fig. 12. A wide stop band can be seen starting from approx. 300 Hz. Due to the high amount of damping all peaks above the stopband are damped. This effect is even more significant in the experiment than in the numerical prediction.

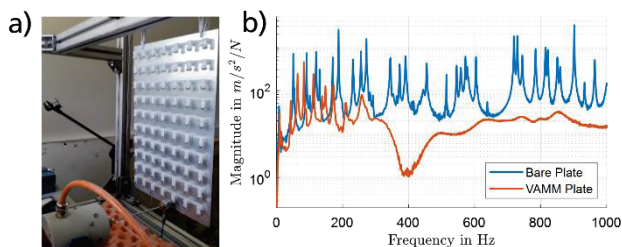


Figure 12: Experimental validation of plastic concept demonstrator plate - a) excitation of plate in free velocity boundary conditions and b) stop band behavior in magnitude of averaged acceleration frequency response function

The experimental investigations show that the stop band behavior could be validated for both concepts.

Conclusion & Outlook

To conclude the paper an evaluation of the proposed concepts is performed. Both concepts were design for large-scale production of resonator compounds. A stop band behavior could be seen in the numerical simulation as well as in the experimental validation for both concepts. The Metal Concept shows a low damping behavior and a deeper stop band, whereas the plastic concept shows a wider and less deep stopband due to higher damping. For the metal concept the manufacturing process using punching and bending machines could also be validated. For the plastic concepts a transition to Injection Molding for large-scale production is planned. Further Investigations have to be made on the role of uncertainties in the punching and bending process for the metal concepts as well as the injection molding process for the plastic concept. Also, a transition to more complex base structures is considered. After validating the concepts on single- and double-curved demonstrator plates, the metal door frame will be considered as the target structure.

ACKNOWLEDGEMENT

This work was supported by the Fraunhofer Internal Programs under Grant No. PREPARE 840224

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